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Original Article

Low-cost sensors and microcontrollers as irrigation management tools[1]

Sensores e microcontroladores de baixo custo como instrumentos de manejo de irrigação

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HIGHLIGHTS:

The soil moisture sensor allowed efficient measurement of soil moisture after calibration.
Economically, there was greater growth and production of lettuce and, environmentally, greater efficiency in water use.
Socially, the device promotes improvements in the farmer's living conditions, directing him to plan activities in the field.

ABSTRACT: Water is the resource that contributes the most to crop development. However, quantity and quality need to be improved, especially in semiarid regions, which makes it important to use techniques that allow rational use, especially in sensitive crops, such as lettuce. Thus, the objective was to apply a system for monitoring soil moisture, in addition to the volume of water applied through irrigation, for rural producers in the semiarid region, using low-cost sensors to cultivate leaf lettuce under irrigation depths. For this purpose, an experiment was conducted with a randomized block design in a strip-plot scheme, with five irrigation depths corresponding to 50, 100, 160, 250, and 380% determined based on the level of water replacement used in irrigation management carried out empirically by the producer, in the control range (100%), corresponding to 190 mm, with 5 replicates. These irrigation depths were monitored for soil water content using low-cost moisture sensors (HD-38) with integrated circuits (LM 393) at depths of 0 to 20 cm and 20 to 40 cm in lettuce cultivation carried out in beds. The resistive sensor allowed accurate measurement of soil moisture after calibration. The highest lettuce production and highest water use efficiency were obtained with the 723 and 95 mm irrigation depths, respectively.

Key words: *Lactuca sativa* L., water limitation, soil moisture

RESUMO: A água é o recurso que mais contribui para o desenvolvimento das culturas. No entanto, a quantidade e qualidade precisam ser melhoradas, em especial em regiões semiáridas, o que torna importante o uso de técnicas que permitam o uso racional, principalmente em culturas sensíveis, como a alface. Assim, objetivou-se aplicar um sistema de monitoramento da umidade do solo, além do volume de água aplicada via irrigação, para produtores rurais da região semiárida, utilizando sensores de baixo custo para o cultivo de alface Crespa, sob lâminas de irrigação. Para tanto, foi conduzido um experimento com delineamento em blocos casualizados em esquema de faixas, com cinco lâminas de irrigação correspondentes a 50, 100, 160, 250, 380% determinadas com base no nível de reposição hídrica utilizado no manejo de irrigação realizado de maneira empírica pelo produtor, na faixa de controle (100%) correspondente a 190 mm, com 5 repetições. Essas lâminas de irrigação foram monitoradas quanto ao teor de água do solo por meio de sensores de umidade de baixo custo (HD-38) com circuito integrado (LM 393) nas profundidades de 0 a 20 cm e de 20 a 40 cm no cultivo de alface realizado em canteiros. O sensor de umidade do solo permitiu uma medição precisa da umidade do solo após a calibração. A maior produção de alface, e a maior eficiência no uso da água foram obtidas com o uso das lâminas de 723 e 95 mm, respectivamente.

Palavras-chave: *Lactuca sativa* L., limitação hídrica, umidade do solo

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Introduction

Artificial water application is essential for agricultural production, especially in arid and semiarid regions like the Brazilian Northeast, which has a negative water balance (Lucena et al., 2023). In this region, precipitation ranges from 200 to 800 mm, and evapotranspiration rates range from 1,800 to 2,600 mm, concentrated in two to four months during the year (Tinôco et al., 2018).

The report by the National Water Agency (ANA, 2021) shows that irrigated agriculture accounts for 68.4% of water consumption in Brazil. Out of the total of 2,082.7 m^3 s^{-1} withdrawn from water bodies, 1,157.9 m^3 s^{-1} are allocated to irrigation (ANA, 2021), highlighting the importance of using this resource efficiently, especially in the Brazilian semiarid region.

Irrigation management based on intelligent monitoring and control strategies enhances irrigation scheduling in open-field agricultural systems, improving water use efficiency (Bwambale et al., 2022). For direct and more precise monitoring, gravimetry would be necessary, which, besides being more expensive, has a temporal limitation. Therefore, the use of capacitive sensors, calibrated for the specific conditions of use, is a way to ensure monitoring with good precision in various horticultural crops and with low construction costs (Campos et al., 2021; Mendes et al., 2021; Li et al., 2022).

Consequently, the use of soil moisture sensors has special potential for the cultivation of vegetables by small producers, such as lettuce (*Lactuva sativa* L.), a crop whose quality and yield are related to high water needs, which requires frequent and abundant irrigation, mainly due to high evapotranspiration and a small and fragile root system (Farias et al., 2015). In this way, care should be taken with the proper application of water to obtain economically viable yields and greater water use efficiency. Thus, the calibration of soil moisture sensors for the cultivation conditions of these plants is necessary, as each soil's chemical, physical, and biological specificities are to be monitored (Szypłowska et al., 2021).

Therefore, the objective was to apply a low-cost system for monitoring soil moisture and the volume and flow rate of irrigation water by family farmers in the semiarid region to cultivate leaf lettuce under irrigation depths.

Material and Methods

The experiment was conducted on a property located in the municipality of Nossa Senhora da Glória, Sergipe state, Brazil (10° 12' 28" S, 37° 25' 19" W, 268 m of altitude), with an area of 0.15 ha (Figure 1). According to Köppen's classification, the region's climate is of the As type, meaning tropical with a dry summer (Sousa & Brito, 2022). During irrigation management, with the use of the sensor, precipitation of 159 mm was recorded during the period, with a maximum of 59.5 mm per day, and minimum temperature of 19.26 °C, and a maximum of 33.76 °C. Climatic irregularities are typical of semiarid regions, consisting of two well-defined climatic conditions: dry and rainy (Leite et al., 2018).

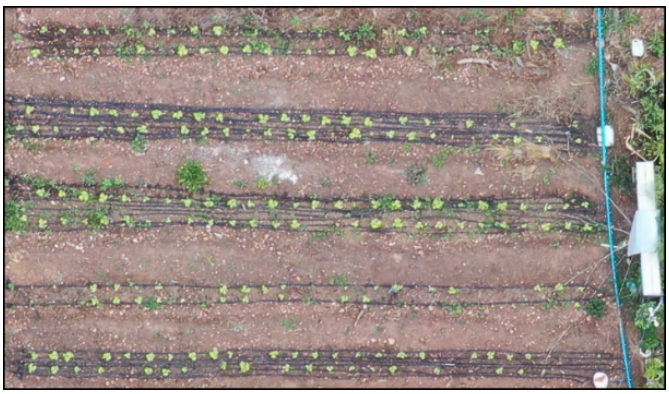


Figure 1. Overview of the experiment obtained by an unmanned aerial vehicle

Initially, for bed soil preparation, sawdust, dry foliage, cattle and sheep manure, charcoal, and 20 L of biofertilizer prepared at a ratio of 1 L of homemade organomineral fertilizer to 19 L of water were used as fertilization. As top-dressing, organomineral fertilizer, produced from brown sugar, rock powder, and soil collected from Caatinga litter, was applied. Additionally, 15 days after lettuce planting, each bed was covered with two bags of crushed corn silage.

All other cultivation practices, such as weed management and pest control, were carried out based on daily monitoring of the plants.

The cultivation of leaf lettuce was studied under five irrigation depths (95, 190, 304, 475, and 723 mm) using a randomized block design in a strip-plot scheme, with 5 replicates. Five beds were used for the distribution of treatments, each corresponding to an irrigation depth, which was measured based on the water replacement level used in the irrigation management of the producer in the control strip (100%), corresponding to 190 mm, according to their common sense.

The bed was constructed with a width of 1 m and a length of 10 m, divided into five parts, each corresponding to a replicate (plot), where leaf lettuce was planted, distributed in two rows, with a spacing of 0.40 m between plants and rows. Thus, the five treatments were replicated in five blocks, totaling 25 plots, with the experimental unit consisting of 10 plants in total, of which three were selected as applicable, and irrigated with the drip system, activated by gravity.

Table 1 shows the results of the irrigation system uniformity test and also includes the irrigation depths applied in each bed, considering the farmer's flow rates and irrigation times, which resulted in one irrigation depth lower than the one applied by the farmer and three higher irrigation depths. It is worth noting that the irrigation depth applied by the farmer was determined empirically, leading to more significant variability.

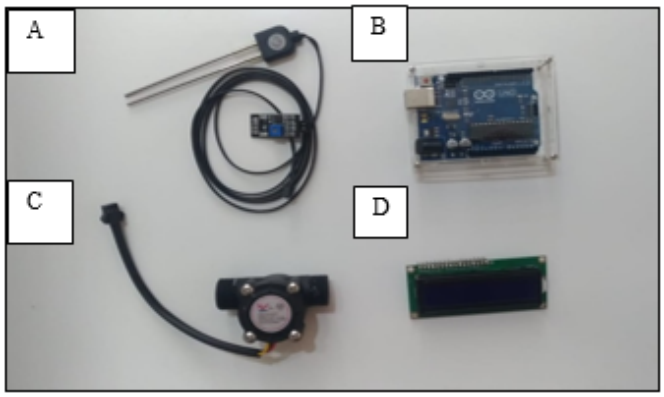
The moisture sensors, flow and volume sensors, as well as the low-cost microcontroller (Figure 2), were installed on 01/29/2022, after the farmer had already prepared the soil for the blocks that received the lettuce seedlings.

Then, moisture sensors (HD-38) with integrated circuit (LM 393) were installed, five at each depth from 0 to 20 cm and 20 to 40 cm (Figure 3) to read the variation in soil moisture in each cultivation strip (irrigation level), i.e., each bed had two moisture sensors, one at each soil depth.

Table 1. Evaluation of the uniformity of a drip irrigation system for lettuce cultivation

Bed	Flow rate (L h^{-1})	CUC (%)	Classification*	Irrigation depth (%)	Number of tapes	Irrigation depth (mm)
1	0.306	89.77	Great	100	6	190
2	0.449	93.82	Excellent	50	2	95
3	0.579	91.35	Excellent	250	8	475
4	0.697	92.58	Excellent	380	10	723
5	0.733	91.40	Excellent	160	4	304

*Recommended classification according to Bernardo et al. (2019); CUC - Christiansen's Uniformity Coefficient



A: HD-38 soil moisture sensor; B: Arduino microcontroller; C: YF-S201 water flow and volume sensor; D: 1602A (liquid crystal display)

Figure 2. Images of the instruments that composed the soil moisture monitoring system

Figure 3. Images of soil moisture sensors being installed in the field

The Arduino microcontroller (from Arduino©) (Figure 2B) received information from the sensor every 5 min. It is transmitted to an integrated liquid crystal display or LCD (1602A) (Figure 2D) for reading and indication of information about the timing of irrigation and the desirable water volume to reach field capacity. The Arduino microcontroller was also coupled with a voltage regulator to prevent equipment burnout, as a 32-volt DC source powered the entire system.

The communication between the Arduino microcontroller and the ScadaBR software (OpenSource, developed by Sensorweb©), present in the Supervisory Control and Data Acquisition (SCADA) system, was carried out using a Modbus protocol (Modbus Organization©), allowing both the acquisition and storage of data obtained by the sensors in the SCADA.

The water flow and volume sensor (YF-S201) (Figure 2C) was connected to the drip tape (spacing of 0.2 m between emitters), immediately after its calibration, based on the manufacturer's calibration data, see Eq. 1, to monitor the flow rate and volume of water applied by the irrigation system.

$$f = k \times Q \quad (1)$$

where:

f - frequency (Hz);

k - calibration constant (dimensionless); and,

Q - flow (L min^{-1}).

After preparing the beds, undisturbed soil samples were collected from each bed at depths of 0-20 cm and 20-40 cm using an Uhland-type auger. The samples were sent to the Soil Laboratory of the Department of Agronomic Engineering at the Federal University of Sergipe, São Cristóvão Campus, where physical-hydraulic analyses were performed.

The physical-hydraulic analyses performed in the laboratory corresponded to texture analysis, with the data described in Table 2, which in general showed that the soil can be classified as loamy sand from 0 to 20 cm and as sandy loam from 20 to 40 cm.

Soil bulk density was determined using data from undisturbed soil samples from each bed, obtaining the soil volume and dry weight. The averages of the samples from depths from 0 to 20 cm and from 20 to 40 cm are shown in Table 2. However, for sensor calibration, the density value of each bed was considered separately for the conversion of moisture on a weight basis to moisture on a volume basis, and the calibration was performed using the response of the resistive sensor in terms of the analog output signal.

The calibration curves of the soil moisture sensors were performed using the actual soil moisture obtained by the gravimetric method (standard oven method) (Bernardo et al., 2019) and from the interpolation (Figure 4) of the conversion of the analog signal (0-1023) to percentage values (0-100%) obtained for the equipment.

Table 2. Particle-size distribution and classification of collected soils

Layer (cm)	Texture (%)			d_s (g dm^{-3})	Texture classification
	Sand	Clay	Silt		
0-20	85.82	8.30	5.88	1.51	Loamy Sand
20-40	69.46	17.79	12.75	1.69	Sandy Loam

d_s - Soil bulk density

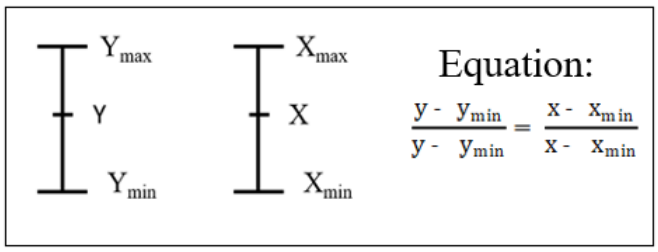


Figure 4. Interpolation of analog signal conversion to percentage

The leaf lettuce seedlings were obtained from a commercial nursery and transplanted when they were 23 days old after sowing in 200-cell polyethylene trays when the plants had two true leaves.

The seedlings were transplanted to beds prepared in soil classified as Plinthosol with a sandy loam texture (Santos et al., 2018), which according to the characterization of its diagnostic horizons and particle-size analysis, generally remains saturated with water during some periods of the year. In addition, the iron contained is normally segregated in the form of mild redox concentrations, generally with more or less clayey, red, or dark red concentrations (Soil Survey Staff, 2022).

At 23 days after the start of the treatment application, when the plants were ready for harvest, three plants from each plot were collected and taken to the multi-user laboratory of the Federal University of Sergipe, Campus do Sertão, where growth, physiological, and production variables were determined.

The growth variables were the average head diameter (cm), the average stem diameter (cm), and the plant leaf area (cm^2), measured using a ruler graduated in centimeters, a digital caliper graduated in millimeters (Stainless Hardened), and a portable leaf area meter (Cl-202 Laser Area Meter), respectively. Additionally, the specific leaf area (g cm^{-2}) was estimated using the leaf area and dry weight of the sample per plant.

The growth analysis determined the number of leaves per plant (leaves larger than 3 cm) and the dry weights of the leaves, roots, and stem (g per plant). To obtain the dry weights of the leaves, roots, and stem, the partitioned materials were placed in paper bags, identified by treatment, block, and plant, and dried in an oven at a temperature of ± 65 °C for 72 hours to reach a constant weight. The dried material was weighed using a digital scale (AD3300) with a precision of 0.01 g.

The total chlorophyll content (μg cm^{-2}) and the SPAD chlorophyll index (SPAD) were measured on the first mature leaf from the apex of the leaf rosette using a portable chlorophyll meter (atLEAF CHL PLUS).

Lettuce yield (Y) (g per plant) was determined from the fresh weight of the aboveground part (g) (FWAP) and the root (g) (FWR), measured using a digital scale (AD3300) with a precision of 0.01 g.

The fresh weight of the aerial part (FWAP) and the irrigation depth applied in each irrigation level (Id) were used to determine the water use efficiency (WUE) using Eq. 2.

$$WUE = \frac{FWAP}{Id + Pe} \quad (2)$$

where:

WUE - water use efficiency (g mm^{-1});

FWAP - fresh weight of the aboveground part (g);

Id - irrigation depth (mm); and,

Pe - effective precipitation (mm).

The analysis of the moisture sensor was performed by measuring the coefficients of determination between the analog signal data 0-1023, dimensionless (obtained from the 10-bit resolution of the microcontroller) soil moisture data, completing the data calibration of the sensors.

The data from lettuce cultivation under irrigation levels were initially subjected to the Shapiro-Wilk normality test ($p \leq 0.05$) and then to the analysis of variance using the 'F' test ($p \leq 0.05$). When the irrigation level factor was significant, the variables were evaluated using linear and quadratic regression analysis with F test ($p \leq 0.05$) using Sisvar 5.8 software (Ferreira, 2014).

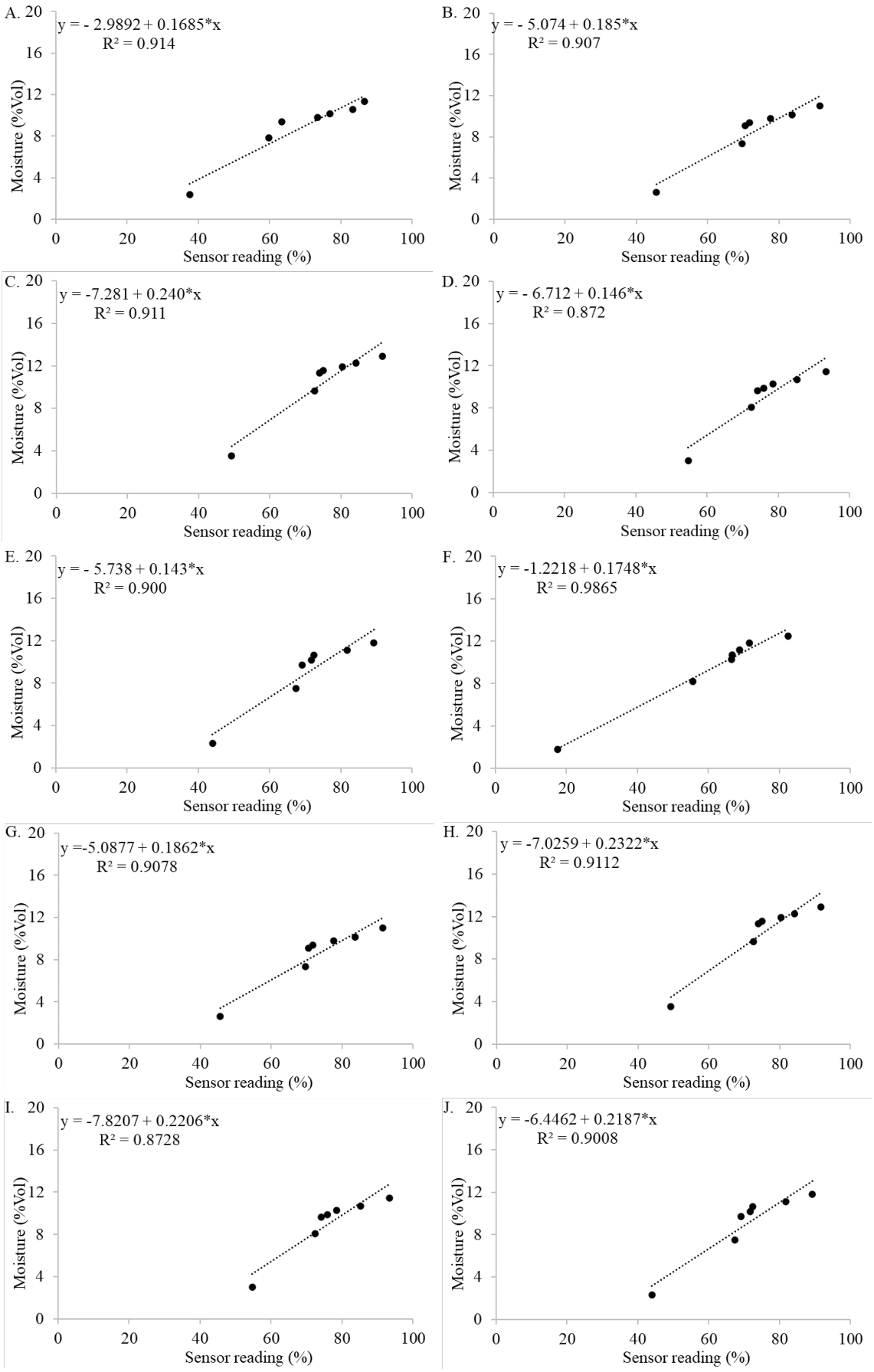
Results and Discussion

The relationship between the analog signal values obtained from the sensors and the actual soil moisture values allowed the construction of the calibration curves shown in Figure 5. It can be noted that the coefficients of determination (R^2) were above 0.87, indicating a predictive and significant relationship. This relationship is important to better estimate soil moisture, as done by Antunes Júnior et al. (2018).

Furthermore, a positive relationship was observed, indicating that increased sensor values correspond to higher moisture readings, demonstrating the equipment's sensitivity (Figure 6). However, the regression equations did not show a strong fit to the soil moisture data from the 0-20 cm depth before and after irrigation. After irrigation, the relationship was described by the equation $y = 11.5 + 0.0016^{ns}x$, with a coefficient of determination (R^2) of 0.1872. Before irrigation, the equation $y = 5.073 + 0.0007^{*}x$ yielded an even lower R^2 value of 0.0824 (Figure 6A). In contrast, at the 20-40 cm depth, a better fit was obtained for the moisture data before irrigation, described by the quadratic equation $y = 2.5952 + 0.0225^{*}x - 0.00003^{*}x^2$, with a R^2 value of 0.533 (Figure 6B).

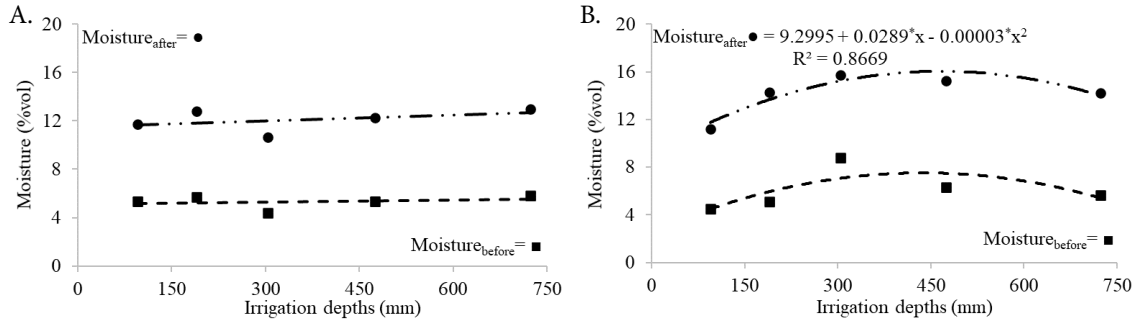
The predictive and positive relationship can be attributed to the protocols used for sending information from the sensor, which was read and transcribed on the Arduino. Additionally, care was taken to correlate the data by sensor installation position (bed), as observed by Pizetta et al. (2017), who proposed calibrating a sensor based on Frequency Domain Reflectometry to three soil classes in Lavras, MG, Brazil, and found a decreasing response for volumetric moisture content as a function of the material's reading (bytes), along with lower coefficient of determination values. This sensitivity of the sensor to soil conditions suggests the need for calibration specific to the location.

Calibration should, therefore, follow the local situation where the equipment is to be installed. Thus, Szypłowska et al. (2021) highlight that the apparent dielectric constant is dependent on the volumetric water content of the soil. They also considered the dielectric constant to be almost



* - Significant at $p \leq 0.05$ by F test

Figure 5. Calibration curves between sensor readings (%) and soil moisture values (Moisture, %Vol) obtained by the gravimetric method, adjusted according to the soil bulk density of beds 1 (A), 2 (B), 3 (C), 4 (D), and 5 (E), obtained at a depth of 0-20 cm, and 1 (F), 2 (G), 3 (H), 4 (I) and 5 (J), obtained at a depth of 20-40 cm, from undisturbed soil samples from the lettuce production area



* - Significant at p ≤ 0.05 by F test

Figure 6. Regression analysis relative to soil moisture estimated by the sensors before and after irrigation when installed at soil depths of 0-20 cm (A) and 20-40 cm (B) under irrigation depths applied

independent of soil texture, density, salinity and organic matter content. Therefore, even for sensors produced by industrial factories, the manufacturer's standard has been shown to be less efficient. With an increase in soil moisture, there is no accurate extrapolation in the reading by the material (Antunes Júnior et al., 2018), as was done in this study.

With calibration and monitoring, it was possible to identify, in each cultivation strip (irrigation depth), at soil depths of 0-20 cm and 20-40 cm, the soil moisture values during the cultivation interval. Using these data, the average moisture before and after irrigation was determined for each strip. The data are shown in Figure 6, where it can be noted that there was a small variation in soil moisture at a depth of 0-20 cm. However, there was an increase in soil moisture at a depth of 20-40 cm, especially when irrigated with depths higher than 100% of what was applied by the producer, leading to water loss through percolation.

The irrigation depths affected the growth of lettuce plants in head diameter, stem diameter, and leaf area (Table 3), highlighting the importance of water in the process of cell division and expansion, essential for plant growth, as noted by other authors who also studied lettuce plants under different irrigation depths (Valeriano et al., 2016).

The importance of using adequate irrigation depths, as identified in this study, was observed by Demir et al. (2022), who studied the yield, quality, and plant nutrient contents of leaf lettuce under different deficit irrigation conditions, using total and partial root-zone drying techniques, and concluded that the yield values were decreased and changes were experienced with the increase of the water stress.

The increase in water depth applied led to an increase in growth in average head diameter (Figure 7A), average stem diameter (Figure 7B), and leaf area of leaf lettuce (Figure 7C), with increases of 12.15, 18.04, and 19.82%, respectively, for each 100 mm increase in applied water depth. The number of leaves (NL) was described by the equation $y = 13.892 + 0.0075^{**}x$, with a coefficient of determination (R^2) of 0.4216. More growth was observed when applying the highest irrigation depth; although it is much higher than the potential evapotranspiration observed in the region, it can be relative to the high drainage capacity of the soil, which can be observed in Figure 6B, with high moisture values in 20-40 cm depth.

The increase in growth in diameter and leaf area caused by the increase in irrigation depth indicates the importance of water, as also observed by Santos et al. (2015) and Valeriano et al. (2016). However, as observed in Figure 6, the moisture content increased in the 20-40 cm layer up to the depth equivalent to 160% of the producer's recommendation, indicating more significant water loss through percolation. This raises the question that, although more significant growth was obtained using the depth equivalent to 380% of the recommendation, this may be related to other benefits of soil moisture, such as maintaining temperature.

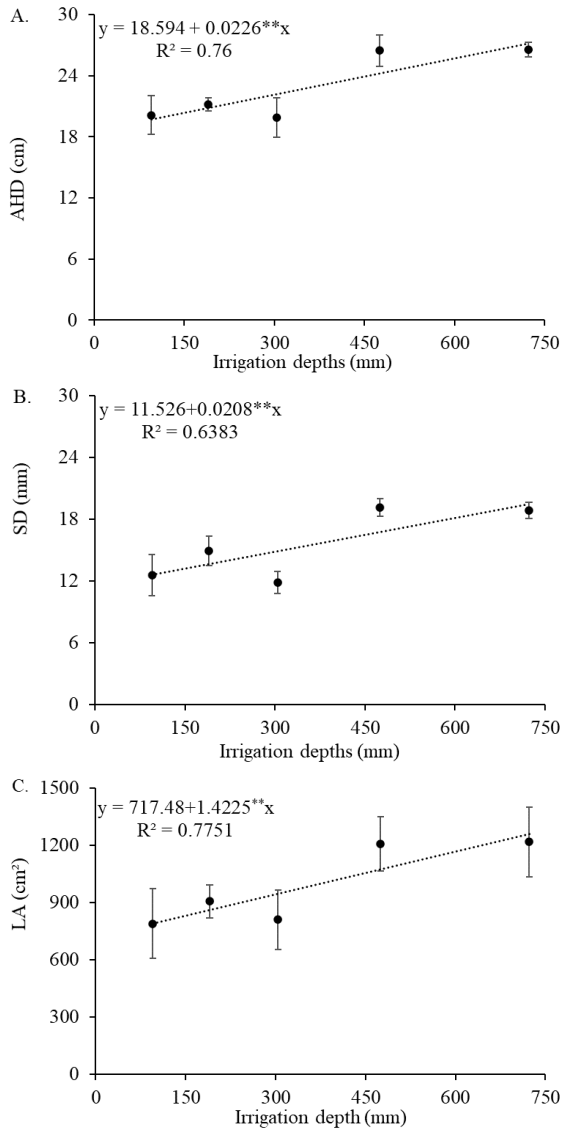
The irrigation depths had an effect on the growth of lettuce plants in terms of the root dry weight, stem dry weight, leaf dry weight, total chlorophyll content, SPAD chlorophyll index, yield and water efficiency use of leaf lettuce (Table 4), indicating the importance of water in the physiological and productive processes of lettuce, as identified by other authors (Silva et al., 2020).

The increase in irrigation depth led to a linear increase in lettuce plant growth in terms of root dry weights ($y = 0.3004 + 0.0004^{**}x$) ($R^2 = 0.5168$). The increase in irrigation depth resulted in a linear enhancement of lettuce growth, as seen

Table 3. Summary of the analysis of variance for the average head diameter (AHD), stem diameter (SD), number of leaves (NL), leaf area (LA), and specific leaf area (SLA) of lettuce under irrigation depths during the field production period

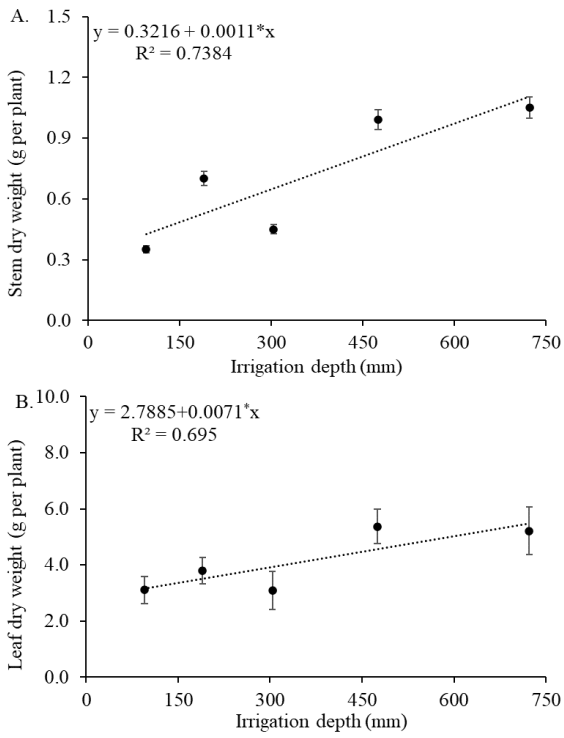
Source of variation	DF	Mean Squares				
		AHD (cm)	SD (mm)	NL	LA (cm²)	SLA (g cm^{-2})
Block	4	2.39^{ns}	1.04^{ns}	2.32^{ns}	8,941.29^{ns}	571.59^{ns}
Error^1	4	2.39	1.04	2.32	8,941.29	571.59
Irrigation depth	4	57.32**	57.74**	41.34**	222,808.03**	973.84^{ns}
Error^2	12	2.01	2.12	3.11	33,581.21	663.17
CV^1 (%)	--	6.76	6.60	9.19	9.60	9.84
CV^2 (%)	--	6.21	9.43	10.64	18.61	10.60
Mean	--	22.85	15.44	16.57	984.90	242.90

DF - Degrees of Freedom; CV - Coefficient of Variation; ^{ns} - Not significant; ** - Significant at p ≤ 0.01 by the F-test



** - Significant at p ≤ 0.01 by the F-test; Vertical bar means standard deviation

Figure 7. Regression analysis for the variables average head diameter (AHD) (A), average stem diameter (SD) (B), and leaf area (LA) (C) of leaf lettuce under irrigation depths



* - Significant at p ≤0.05 by the F test; Vertical bar means standard deviation

Figure 8. Regression analysis for the variables stem dry weight (A) (g per plant) and leaf dry weight (B) (g per plant) of leaf lettuce under irrigation depths

in stem dry weight (Figure 8A) and leaf dry weight (Figure 8B). The most pronounced response was observed in stem dry weight, which increased by approximately 65% for every 100 mm increment in irrigation depth. In comparison, leaf dry weight exhibited a more moderate increase of 25.4% for each 100 mm additional irrigation. Maximum leaf biomass was achieved at the highest irrigation depth evaluated. This denotes the importance of water availability in the growth process and carbohydrate accumulation, especially in lettuce, which is sensitive to water stress.

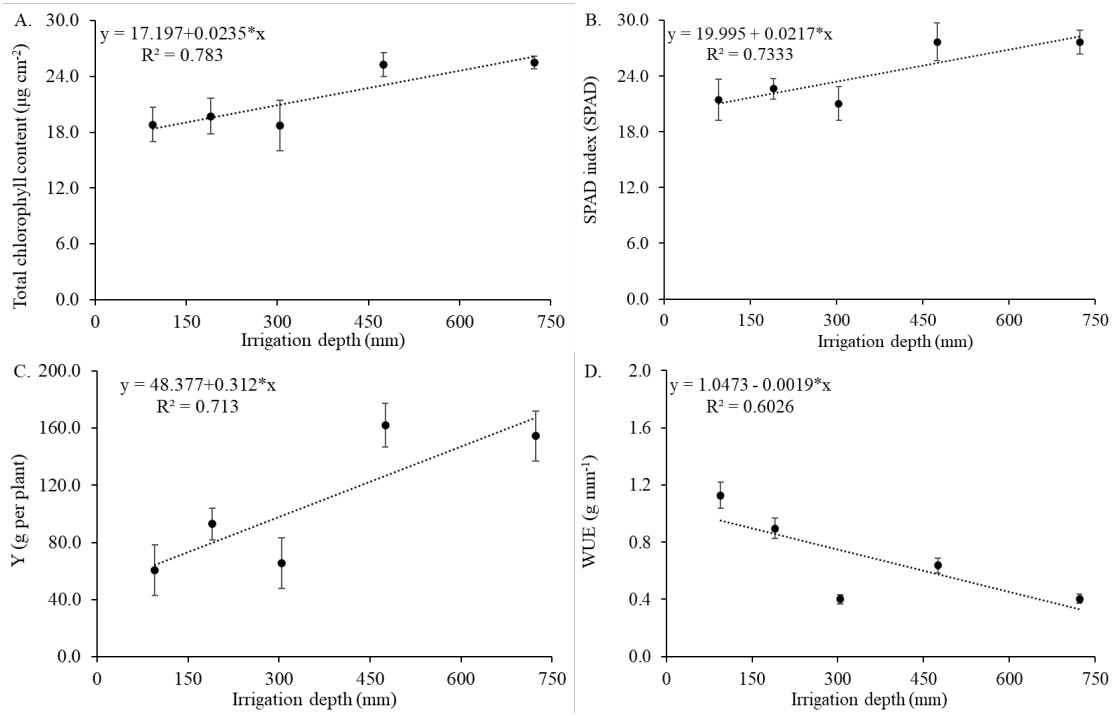
The total chlorophyll content (Figure 9A), SPAD chlorophyll index (Figure 9B), and yield of lettuce (Figure 9C) showed a linear increase with the increase in applied water depth, with increments of 13.66, 10.85, and 64.49% with each 100 mm increase in the water depth, respectively. Lettuce yield was the most sensitive variable to the stress effect, as it represents a cumulative effect.

The observed effect on plant growth and production caused by the water depths can be related to the importance of water in physiological processes since water deficit generates reactions that lead to signaling and production of abscisic acid (ABA), which induces stomatal closure, reducing gas exchange and inhibiting photosynthesis (Taiz et al., 2017; Ouyang & Tian, 2023).

Table 4. Summary of the analysis of variance for the variables root dry weight (RDW), stem dry weight (SDW), leaf dry weight (LDW), total chlorophyll content (TCC), soil plant analysis development index (SPAD), yield (Y), and water use efficiency (WUE) of leaf lettuce under irrigation depths

Source of variation	DF	Mean squares						
		RDW	SDW	LDW	TCC	SPAD	Y	WUE
		(g per plant)			(μg cm^{-2})		(g per plant)	(g mm^{-1})
Block	4	0.0032^{ns}	0.0073^{ns}	0.1685^{ns}	1.54^{ns}	3.45^{ns}	109.20^{ns}	0.021288^{ns}
Error^{1}	4	0.0032	0.0073	0.1685	1.54	3.45	109.20	0.021288
Irrigation depth	4	0.1034**	0.4909**	6.14**	60.01**	54.84**	11,673.53**	0.503616**
Error^{2}	12	0.0113	0.0219	0.5626	4.50	2.76	354.11	0.03172
CV^{1} (%)	--	12.51	12.10	9.97	5.74	7.72	9.76	21.06
CV^{2} (%)	--	23.58	20.93	18.22	9.81	6.90	17.57	25.71
Mean	--	0.45	0.70	4.12	21.61	24.08	107.10	0.69

DF - Degrees of Freedom; CV - Coefficient of variation; ^{ns} - Not significant; ** - Significant at p ≤ 0.01 by the F test



* - Significant at p ≤ 0.05 by the F test; Vertical bar means standard deviation

Figure 9. Regression analysis for the variables total chlorophyll content (A), SPAD chlorophyll index (B), yield - Y (C), and water use efficiency - WUE (D) of leaf lettuce under irrigation depths

Increasing the irrigation depth increases production, as lettuce requires a significant amount of water from planting to harvest, as also identified by Yavuz et al. (2021), who highlighted the impact of water stress on the biochemical and physiological characteristics of lettuce. Although this increase in production is desirable as it adds value to the lettuce (Cassimiro et al., 2020), it was noted in this study that the water consumption for producing higher quality lettuce exceeded 400 mm, a value higher than that usually used by the producer and the reference evapotranspiration of the region for the period, according to INMET data.

The observation of higher production with the most significant irrigation depth leads to another consideration, especially when analyzing the data of soil moisture in the soil layer between 20 and 40 cm, where water accumulation is observed, notably under irrigation depths exceeding 300 mm (Figure 6), which suggests water losses due to percolation.

However, although this occurrence indicated a water loss issue, there was an increase in lettuce yield (Y, g per plant) (Figure 9C), which raises the hypothesis that the benefit of increased irrigation depth may be related to longer infiltration and permanence times, reducing thermal stress, for example. Further research, especially with intermittent irrigation, is needed to verify this theory in the region.

The highest water use efficiency (WUE) is observed with the lowest irrigation depth, about 0.87 g mm^{-1}, under an irrigation depth of 95 mm, with a decrease in WUE values as the irrigation depth increases (Figure 9D). Thus, for every 100 mm increase in irrigation depth, there is an approximate reduction of 0.19 g mm^{-1}, attributed to excess moisture in the root system, making aeration difficult and thus causing anomalies of physiological origin, as observed by some authors (Valeriano et al., 2016; Cassimiro et al., 2020).

Conclusions

1. The resistive sensor allowed accurate measurement of soil moisture after calibration. The highest lettuce production and highest water use efficiency were obtained with the 723 and 95 mm irrigation depths, respectively.

2. More significant lettuce growth and production were achieved with the highest irrigation depth but with water losses due to percolation.

3. Studying more suitable management practices using intermittent irrigation to optimize production and water use is recommended.

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